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Physics Procedia 12 (2011) 462–471

Physics Procedia

LiM 2011

Influence of Intensity Distribution and Pulse Duration on Laser Micro Polishing

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Abstract

Laser micro polishing with pulsed laser radiation is a process to reduce the micro roughness of surfaces. During polishing the properties of the laser radiation have a great influence on the results.
In this publication the influence of the type of intensity distribution (near-Gaussian, top-hat), of its geometry (circular, square), and of the pulse duration (≈100-1400ns) on the roughness of tool steel (1.2343) surfaces is investigated. Additionally, the influence of the pulse duration on the maximal polishable spatial wavelength is examined.

Keywords: laser polishing, pulse duration, intensity distribution

1. Motivation / State of the Art

When using conventional mechanical polishing techniques the polishing process consists of many different grinding and polishing steps. Especially three-dimensional surfaces can only be polished with a very high effort. Often automated machining is not possible due to the avoidance of edge-rounding and the limited accessibility. Then the parts have to be polished manually. Beside the very low polishing rates (typically 10-30 min/cm²) the main disadvantages are the very high costs and the limited repeatability. Additionally, the geometry of parts is changed at least at a micro-scale and so it is difficult to ensure close tolerances.

An alternative approach is polishing with laser radiation [1,2]. The laser radiation, which is moved meanderly over the surface, is used to melt a thin surface layer and the material is smoothened by the surface tension, Figure 1.
Two variants of laser polishing can be distinguished: laser macro polishing with continuous laser radiation and laser micro polishing with pulsed laser radiation. Typical polishing rates are 1min/cm² for laser macro polishing and 3.3s/cm² for laser micro polishing. A space-resolved polishing (selective laser polishing) is possible as well [3].
During laser micro polishing the intensity distribution and the pulse duration are important parameters. In the following investigations the influence of the type of intensity distribution (near-Gaussian, top-hat), of its geometry (circular, square), and of the pulse duration (≈100-1400ns) on the roughness of tool steel (1.2343) surfaces is

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doi:10.1016/j.phpro.2011.03.057

examined. Additionally, the influence of the pulse duration on the maximal polishable spatial wavelength is investigated.

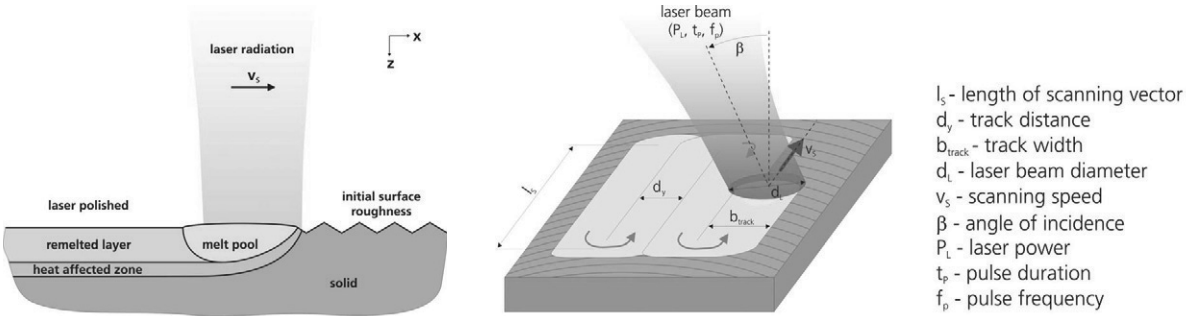
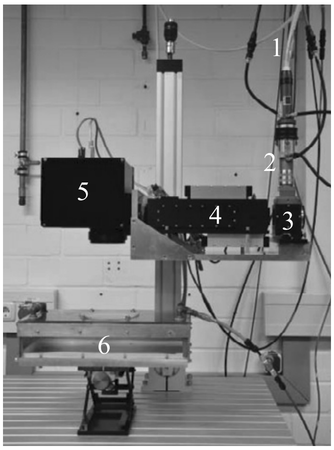


Figure 1. (a) Principle of polishing with laser radiation in cross section; (b) Strategy for moving the laser beam over the surface

2. Experimental setup

The experimental setup (Figure 2) consists of a fiber-coupled (1) laser beam source, a collimation (2), a tilted mirror (3), a laser power attenuator (4), a two-dimensional scan head with f-theta lens (f=163mm) (5), and a process chamber filled with inert gas (argon) (6). The laser radiation is guided to the experimental setup by the fiber, collimated by the collimation, and diverted in the mirror. It runs through the laser power attenuator into the scan head and is focused onto the surface of the workpiece in the process chamber by the f-theta lens. The attenuator enables the variation of the laser power without the variation of the operating point of the laser beam source and so without the variation of the laser pulse duration.

A fiber-coupled disk laser (TruMicro 7050, wavelength λ=1,030nm) and a fiber-coupled rod laser (based on Rofin DY-series, wavelength λ=1,064nm) are used for the experiments. Both lasers are run at two operating points with two different fibers (circular and square profile). The pulse duration t_P (FWHM) at these operating points and the dimensions of the optical fibers are given in table 1. The dependency of the pulse duration on the fiber profile for the disk laser is reproducible and cannot be explained yet.



1: Optical fiber
2: Collimation
3: Tilted mirror
4: Laser power attenuator
5: Scan head
6: Process chamber

Figure 2. Experimental setup

Table 1. Laser pulse duration t_P (FWHM) at the two operating points and dimensions of the optical fibers

	Fiber profile	Operating point 1	Operating point 2
Disk laser	Circular (∅200µm)	1.35µs	1.25 µs
	Square (□300µm)	1.25µs	1.15 µs
Rod laser	Circular (∅300µm)	164 ns	111ns
	Square (□400µm)	164 ns	111ns

For the disk laser the intensity distribution (Figure 3) of the laser radiation in the machining plane is in-between Gaussian and top-hat (in the following described as "near-Gaussian") for the circular fiber profile and close to top-hat for the square fiber profile. The use of these intensity distributions allows the examination of the influence of the type of intensity distribution on the surface roughness during laser micro polishing. The intensity distribution of the laser radiation generated by the rod laser is close to top-hat for both fibers. This allows the investigation of the influence of the geometry (rotation-symmetrical and non-rotation-symmetrical) on the surface roughness.

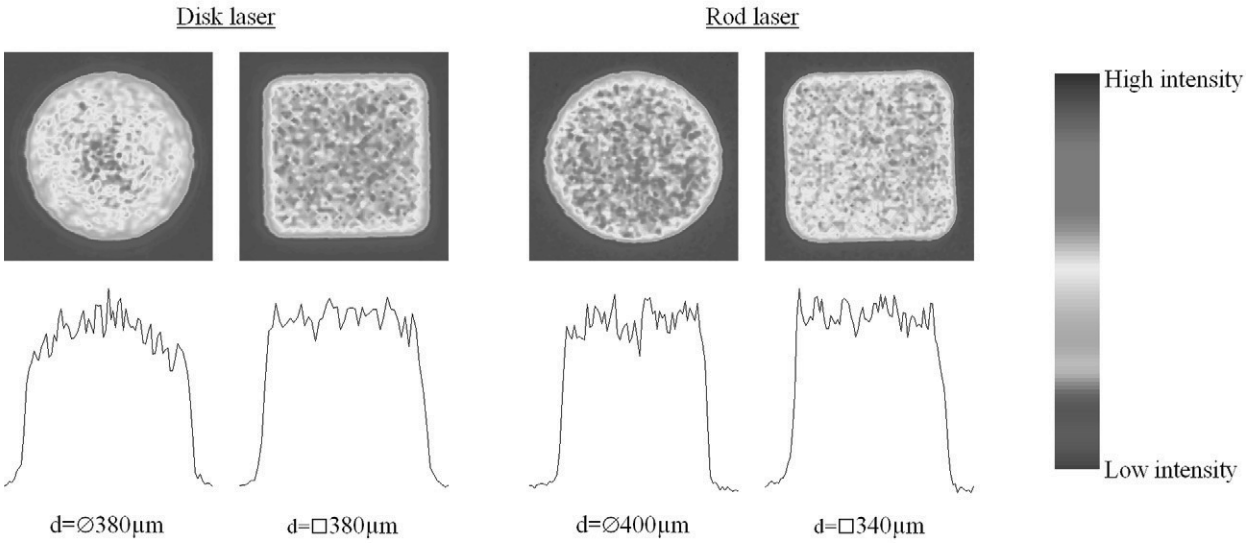


Figure 3. Intensity distribution and laser beam dimensions (86% definition) in the working plane for (a) the disk laser, (b) the rod laser in conjunction with the circular and the square fiber profile

For an estimation of the homogeneity of the intensity distribution a rectangle (Figure 4) can be built up that is defined by the average intensity of the upper 10% of the measuring points $I_{a,upper10\%}$ and the beam diameter (twice the beam radius w_0, 86% definition). With the proportion P of the surface below the graph A_g and the surface area of the rectangle A_r the quality of the intensity distribution can be determined:

$$P = A_g / A_r \tag{1}$$

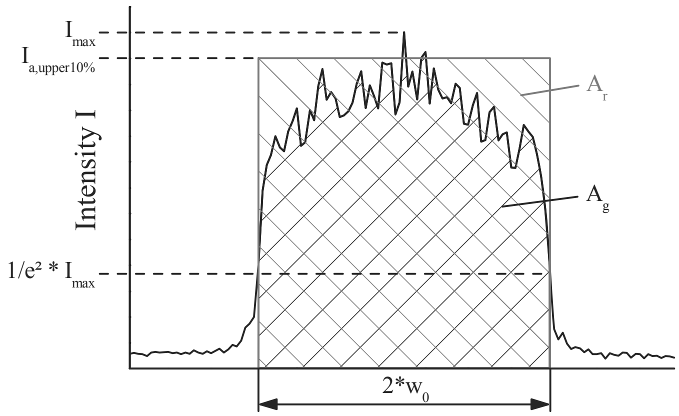


Figure 4. Definition of the proportion P

While an ideal top-hat distribution has a proportion of P=1 the results for the disk and the rod laser are below this value, table 2. For the disk laser the difference between the two profiles is 10%. For the rod laser the difference is <1% and the quality of the intensity distribution can be considered as the same for both geometries.

Table 2. Proportion *P* for the disk laser and the rod laser in conjunction with a circular and a square fiber profile

	Circular fiber profile	Square fiber profile
Disk laser	P = 63.9 %	P = 73.9 %
Rod laser	P = 74.5 %	P = 75.1 %

The investigations of the influence of the intensity distribution and of the pulse duration on the surface roughness are carried out on cw-remelted tool steel (1.2343) surfaces so that a homogeneous initial surface roughness is ensured. The investigation of the influence of the pulse duration on the maximal polishable spatial wavelength is carried out on turned tool steel (1.2343) surfaces with a groove distance of d_{groove}=20µm.

On the initial surfaces 10x10mm² areas are laser micro polished. While the pulse duration stays constant according to table 1 (pulse frequency f_P=20kHz) the average laser power P_L is varied from 42W to 289W. The laser scanner is used with a scan velocity of v_S=1,000mm/s and a track offset of d_y=30µm.

The surface roughness of the initial state and the laser polished areas is analyzed by white-light-interferometry. The data gained by this method is used to determine the roughness in dependency on the spatial wavelength of the roughness by a phase-correct filter with Gaussian loading function according to ISO11562.

For a high significance of the results the laser micro polishing is carried out on three different samples which are measured three times by white-light-interferometry. Afterwards the arithmetic average and the standard deviation are calculated from each set of nine measured values. The roughness spectra of the laser polished areas achieved by this method always show an optimum laser power (highest reduction of the roughness achieved) for the micro roughness. These spectra are compared in the following investigations.

3. Results and discussion

3.1. Influence of the intensity distribution on the surface roughness

At first the influence of the orientation of the square, non-rotation-symmetrical intensity distribution on the surface roughness is examined. Two different orientations are distinguished (Figure 5): An angle α of $\alpha=0°$ and an angle of $\alpha=45°$ between the scan direction and the edge of the rectangle of the intensity distribution.

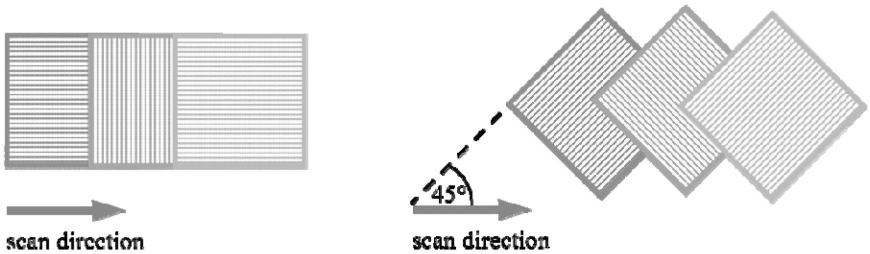


Figure 5: Orientations of the square intensity distribution: (a) angle of $\alpha=0°$, (b) angle of $\alpha=45°$ between the scan direction and the edge of the rectangle of the intensity distribution

Figure 6 shows the roughness spectra of the laser polished surfaces with the lowest micro roughness in dependency on the orientation of the square intensity distribution for the disk laser. While there is no difference in the surface roughness for spatial wavelengths $\lambda \leq 40\mu m$ there is a significant difference of the surface roughness for higher spatial wavelengths. The orientation of $\alpha=0°$ reduces and the orientation of $\alpha=45°$ increases the surface roughness in comparison to the initial state. Hence, an orientation of $\alpha=0°$ is used in conjunction with both lasers for the following investigations.

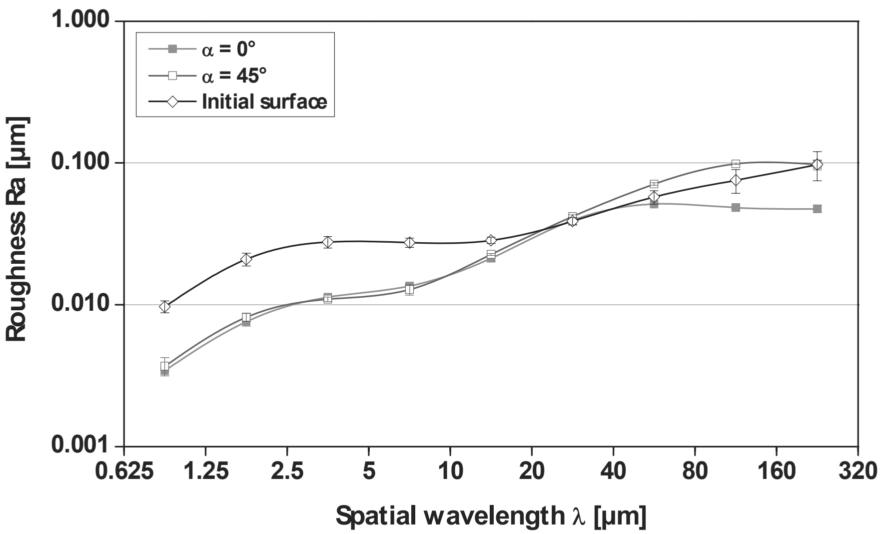


Figure 6. Roughness spectra of the surfaces with the lowest micro roughness in dependency on the orientation between the scan direction and the edge of the rectangle of the square top-hat intensity distribution for the disk laser (P_L=205W, t_p=1.25µs)

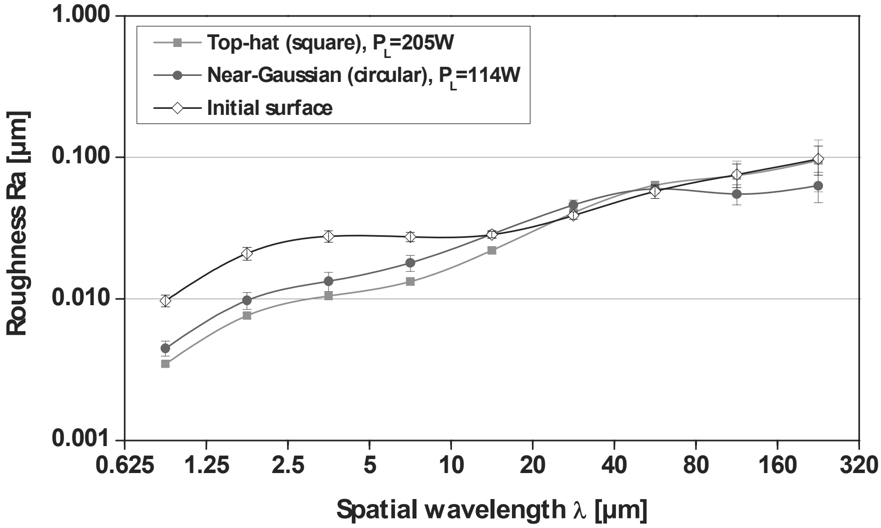


Figure 7. Roughness spectra of the surfaces with the lowest micro roughness in dependency on the type of intensity distribution (near-Gaussian, top-hat) for the disk laser (t_P=1.25µs)

Figure 7 shows the roughness spectra of the laser polished surfaces with the lowest micro roughness in dependency on the type of intensity distribution (near-Gaussian, top-hat) for the disk laser. In contrast to the top-hat distribution the near-Gaussian distribution leads to a higher micro roughness and to an increase of the roughness in comparison to the initial surface for spatial wavelengths between λ=20 and λ=80µm. The reason for the increase seems to be the inhomogeneous intensity distribution that induces surface waves with wavelengths of 20µm≤λ≤40µm in the molten state due to local differences of the vapor pressure. These surface waves are frozen when the material is solidified and induce the surface roughness to increase.

Overall, it can be concluded that a homogeneous intensity distribution leads to a lower surface roughness than a near-Gaussian distribution.

Figure 8 shows the roughness spectra of the laser polished surfaces with the lowest micro roughness in dependency on the geometry of the top-hat intensity distribution (circular, square) for the rod laser. The surface roughness achieved with the square intensity distribution is either as high as the one generated by the circular intensity distribution or it is higher. For spatial wavelengths 20µm≤λ≤80µm there is even an increase of the surface roughness in comparison to the initial state. Figure 9 shows an LM-micrograph of the initial state and the surface laser polished with the circular intensity distribution.

Overall, the results for the rod laser show that the square intensity distribution leads to an increase of the surface roughness in comparison to the initial state for spatial wavelengths 20µm≤λ≤80µm. This effect does not occur when the circular intensity distribution is used. It can be concluded that a circular intensity distribution leads to a lower surface roughness than a square intensity distribution when the quality of these distributions is similar (top-hat).

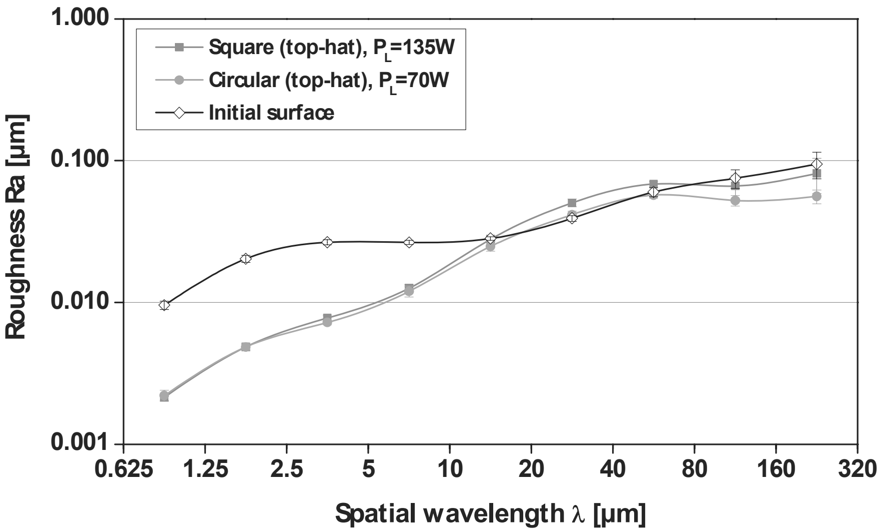


Figure 8. Roughness spectra of the surfaces with the lowest micro roughness in dependency on the geometry of the intensity distribution (circular, square) for the rod laser (t_P=111ns)

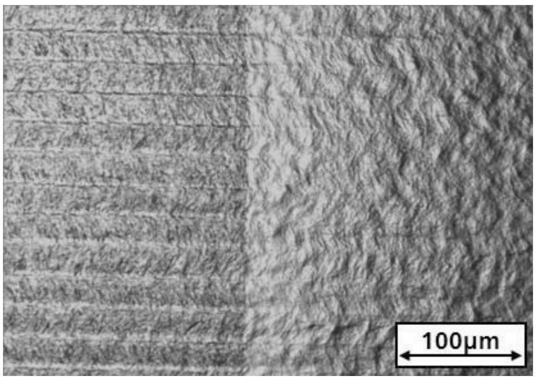


Figure 9. LM-micrograph of the initial state and the surface laser polished with the circular intensity distribution

In summary the investigation of the influence of the type of intensity distribution on the surface roughness shows that the surface roughness that can be achieved with a square intensity distribution is lower if the angle between the edge of the rectangle of the intensity distribution and the scan direction is α=0° (Figure 5). Additionally, it can be concluded that a homogeneous (top-hat) intensity distribution leads to a lower surface roughness than an inhomogeneous distribution (near-Gaussian). The examination of the influence of the geometry of the intensity distribution on the surface roughness revealed that a circular distribution leads to a lower surface roughness than a square distribution if both distributions are homogeneous (top-hat).

3.2. Influence of the pulse duration on the surface roughness

For the investigation of the influence of the pulse duration on the surface roughness a similar intensity distribution is necessary to avoid an influence of the intensity distribution. Hence, the square (top-hat) intensity distribution is used in conjunction with both lasers. Figure 10 shows the roughness spectra of the surfaces with the lowest micro roughness in dependency on the pulse duration.

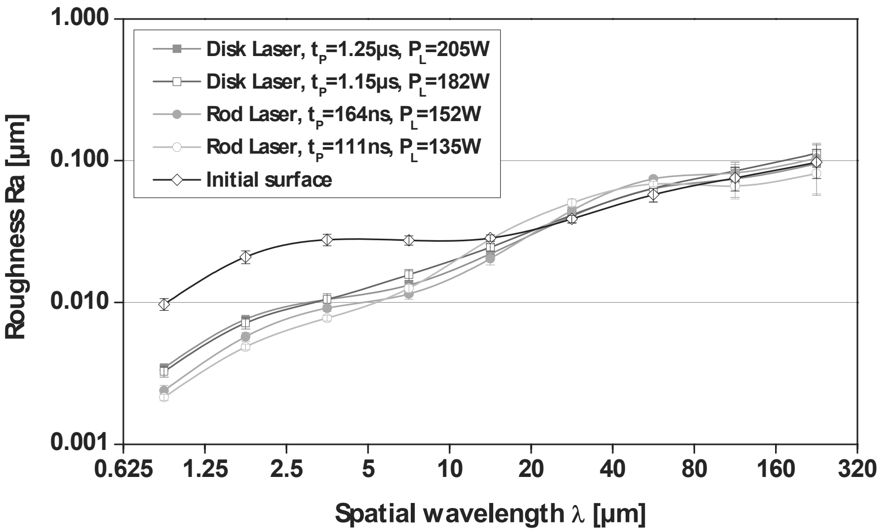


Figure 10. Roughness spectra of the surfaces with the lowest micro roughness in dependency on the pulse duration (square top-hat intensity distribution for both laser beam sources)

The results show that the shorter the pulse duration the lower the micro roughness (λ≤5µm). The difference of the surface roughness achieved is lower for the disk laser than for the rod laser due to the lower relative difference of the pulse duration. For spatial wavelengths 20µm≤λ≤80µm the surface roughness is increased in comparison to the initial surface. This effect is higher for the two short pulse durations (t_P=111ns and t_P=164ns) than for the long pulse durations (t_P=1.15µs and t_P=1.25µs). The reason for this effect seems to be the use of the square intensity distribution (see chapter 3.1).

Overall, it can be concluded that the shorter the pulse duration the higher the reduction of the micro roughness.

3.3. Influence of the pulse duration on the maximal polishable spatial wavelength

The motivation for the investigation of the influence of the pulse duration on the maximal polishable spatial wavelength is to examine if the longer the pulse duration the higher the spatial wavelength that can be smoothed due to the increase of the lifetime of the melt pool during laser micro polishing.

In the investigations of the influence of the intensity distribution on the surface roughness it could be concluded that for the disk laser the square and for the rod laser the circular distribution leads to a lower surface roughness. Hence, for the examination of the influence of the pulse duration on the maximal polishable spatial wavelength these intensity distributions are used in conjunction with the two lasers (pulse duration t_P=164ns for the rod laser, t_P=1.25µs for the disk laser).

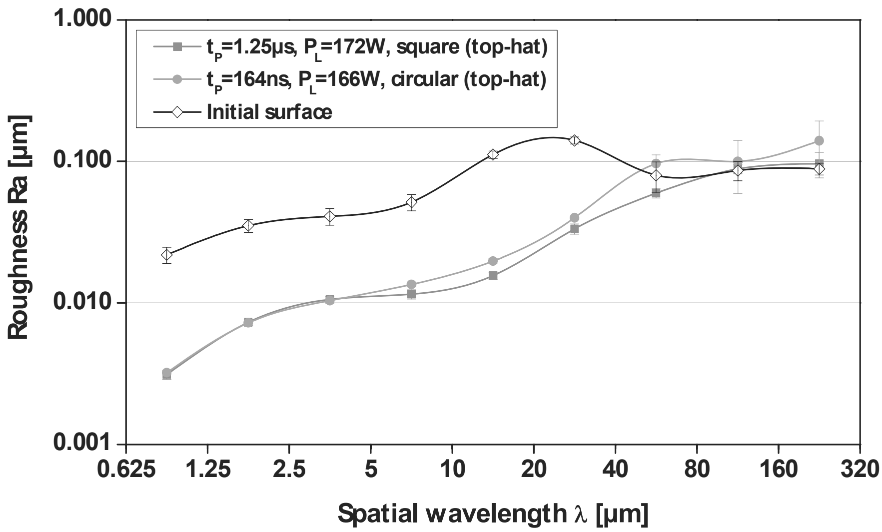


Figure 11. Roughness spectra of the surfaces with the highest maximal polishable spatial wavelength in dependency on the pulse duration

Figure 11 shows the roughness spectra of the surfaces with the highest maximal polishable spatial wavelength. The maximal polishable wavelength regime is λ=40-80µm for the long pulse duration of t_P=1.25µs and λ=20-40µm for the short pulse duration of t_P=164ns. While the micro roughness is similar for both lasers the surface roughness achieved with the rod laser is higher than the one achieved with the disk laser for spatial wavelengths $\lambda \geq$5µm. The roughness for spatial wavelengths 40µm$\leq\lambda\leq$80µm and higher is even increased in comparison to the initial surface when the short pulse duration is used. When the long pulse duration is used the surface roughness is reduced in comparison to the initial state for spatial wavelengths 0.625µm$\leq\lambda\leq$80µm and equates the initial roughness for wavelengths 80µm$\leq\lambda\leq$320µm.

It can be concluded that the maximal polishable wavelength regime increases with a longer pulse duration. Additionally, on a turned surface with a groove distance of d_{groove}=20µm the long pulse duration of t_p=1.25µs leads to a lower surface roughness than the short pulse duration, which causes an increase of the surface roughness in comparison to the initial state for spatial wavelengths $\lambda \geq$40µm.

4. Summary

The influence of the type of intensity distribution (near-Gaussian, top-hat) and its geometry (circular, square) on the surface roughness during laser micro polishing has been investigated. Additionally, the influence of the laser pulse duration on the surface roughness and on the maximal polishable spatial wavelength has been examined.

The investigation of the influence of the intensity distribution showed that a homogeneous (top-hat) distribution leads to a lower surface roughness than a near-Gaussian distribution. Additionally, it has been revealed that a homogeneous, circular intensity distribution leads to a lower surface roughness than a homogeneous, square distribution. When the square intensity distribution was used the surface roughness achieved was lower when the angle between the edge of the rectangle of the intensity distribution and the scan direction was α=0° instead of α=45.

The examination of the influence of the pulse duration on the surface roughness showed that the shorter the pulse duration the higher the reduction of the micro roughness. However, the surface roughness was increased in comparison to the initial state for spatial wavelengths 20µm$\leq\lambda\leq$80µm when the pulse durations of t_P=111ns and t_P=164ns were used. For the pulse durations of t_P=1.15µs and t_P=1.25µs this effect was much lower. The increase of the surface roughness was traced back to the use of the square intensity distribution.

The investigation of the influence of the pulse duration on the maximal polishable spatial wavelength showed that the longer the pulse duration the higher the maximal polishable spatial wavelength. Additionally, the long pulse duration of t_P=1.25µs led to a lower surface roughness than the short pulse duration of t_P=164ns, which caused an increase of the surface roughness in comparison to the initial state for spatial wavelengths $\lambda \geq 40 \mu m$.

Acknowledgements

This work is based on the results of the InnoNet project "MediSurf" funded by the German Ministry of Economics and Technology and executed by VDI/VDE Innovation + Technik. The authors would like to thank both institutions for their generous sponsorship.

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